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AFRL-SR-BL-TR-00-

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1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE		3. REPO.	
				01 Jun 97 to 31 May 00 Final	
4. TITLE AND SUBTITLE 97-AASERT Higt Current Oxide Cathodes				5. FUNDING NUMBERS 61103D 3484/TS	
6. AUTHOR(S) Dr. N. C. Luhmann, Jr.					
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of California, Davis 410 Mrak Hall Davis, CA 95616-8671				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AFOSR/NE 801 North Randolph Street, Rm 732 Arlington, VA 22203-1977				10. SPONSORING/MONITORING AGENCY REPORT NUMBER  F49620-97-1-0393	
11. SUPPLEMENTARY NOTES					
12a. DISTRIBUTION AVAILABILITY STATEMENT Distribution Unlimited, approved for public release				12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) The aim of the AASERT supported research is to develop the plasma deposition/implantation process for coating barium, strontium and calcium oxides on nickel substrates and to perform detailed surface analysis of the resultant materials as well as complete cathode lifetime and performance studies. The vacuum are plasma deposition gun developed at Lawrence Berkeley National Laboratory (LBNL) has been used to deposit oxides and nitrides with very precise control over deposition rate and composition.					
20001120 209					
14. SUBJECT TERMS				15. NUMBER OF PAGES	
				16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT  UNCLASSIFIED		18. SECURITY CLASSIFICATION OF THIS PAGE  UNCLASSIFIED		19. SECURITY CLASSIFICATION OF ABSTRACT  UNCLASSIFIED	
				20. LIMITATION OF ABSTRACT  UL	

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Standard Form 298 (Rev. 2-89) (EG)  
Prescribed by ANSI Std. Z39.18  
Designed using Perform Pro, WHS/DIOR, Oct 94

# **HIGH CURRENT OXIDE CATHODES**

Final Technical Report  
Submitted to:

**Dr. Robert Barker**  
**Contract Monitor**

**AFOSR AASERT Grant F49620-97-1-0393**

**P.I. Professor N.C. Luhmann, Jr.,**  
**University of California, Davis**

**Report Period: 6/1/97-5/31/00**

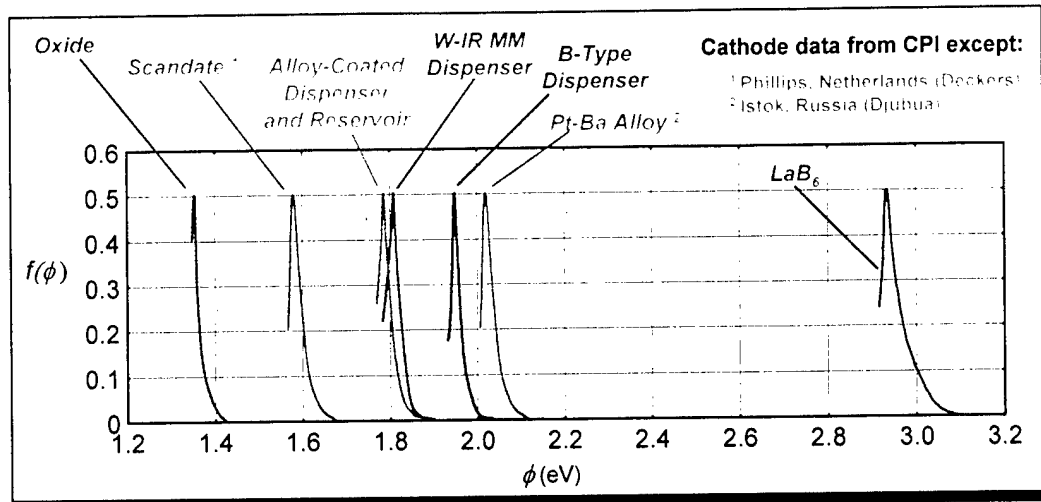
## Introduction

The University of California at Davis (UCD) and Stanford University have been collaborating in alternate cathode technology with the aim of developing a reproducible, robust, high current density oxide cathode. Funding for the equipment has been provided under the DURIP and MURI programs. Oxide cathodes have always had attractively low work functions, but they have been plagued by their variability in performance. The current oxide cathode manufacturing process either paints or sprays a barium-strontium carbonate emission layer on a nickel cathode base. The carbonate powders are mixed with a nitrocellulose binder to provide adhesion to the nickel surface. In order to activate the cathode, the nitrocellulose must be burned off and the carbonates converted to oxides by heating the cathode and drawing a current in vacuum. This activation process deposits byproducts on nearby surfaces that act as poisoning agents when they re-deposit on the cathode surface. An early experiment was performed by Sperry<sup>1</sup> in which the activation was done in a separate chamber and then the cathode was mounted in a clean gun structure. The pulsed emission current from the experimental cathode exceeded 100 A/cm<sup>2</sup> compared to 15 A/cm<sup>2</sup> for the standard oxide cathode.

The aim of this AASERT supported research is to develop the plasma deposition/implantation process for coating barium, strontium and calcium oxides on nickel substrates and to perform detailed surface analysis of the resultant materials as well as complete cathode lifetime and performance studies. Plasma deposition/implantation of the oxide layer directly on the cathode surface will eliminate the major sources of cathode poisoning. The vacuum arc plasma deposition gun developed at Lawrence Berkeley National Laboratory (LBNL) has been used to deposit oxides and nitrides with very precise control over deposition rate and composition. In order to develop this process, significant research is being done on oxide deposition, filtering of macroparticles, concurrent deposition from multiple metal arc sources, plasma chemistry, and deposition of reactive metals. Oxide cathodes produced with this technique may have significantly improved emission properties and certainly will have consistent performance due to the control of the deposition/implantation process. To conduct this research UCD employed an available dedicated, fully-instrumented, computer-controlled ultra high vacuum (UHV) surface analysis station, cathode lifetest characterization instrumentation, and a new plasma deposition system, much of which was provided under the DURIP and MURI programs.

A definitive understanding of the chemistry of oxide cathode operation has yet to be achieved. The widely accepted model of high current density flow through the oxide coating relies on electron conduction through the pores in the coating left behind when the carbonates are converted into oxides;<sup>5</sup> however, Russian work on molecularly-deposited and pressed-porous oxide cathodes<sup>6</sup> has led to equal, and even improved, emission characteristics without the presence of the electron gas-filled pores. These encouraging results for nonporous oxide coatings, combined with the promise of a repeatable process for depositing a precisely controlled oxide coating, make a vacuum arc plasma deposited oxide cathode an exciting alternative to the traditionally spray-coated oxide cathode. Fig.1 is a comparison of the performance of various thermionic emitters in terms of their practical work function distribution. Clearly, a reliable oxide cathode

holds the most promise for achieving high current densities at low operating temperatures.



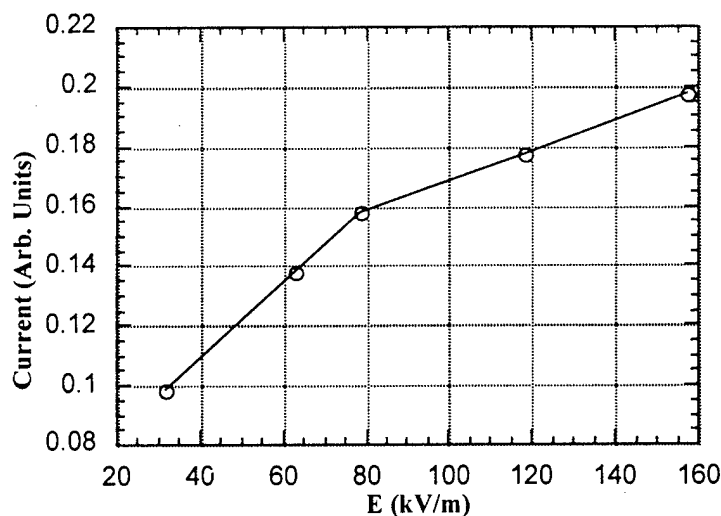
**Figure 1 Practical work function distribution for various thermionic cathode types. Data from CPI cathode life tests except (1) Deckers (Phillips, Netherlands) and (2) Djubus (Istok, Russia). After Cattelino and Miram.<sup>7</sup>**

### Plasma Deposition of Oxide Cathodes

In July of 1996, the UC Davis/Stanford Linear Accelerator Center (SLAC) team began working directly with Dr. Ian Brown of Lawrence Berkeley National Laboratory (LBNL) to evaluate the feasibility of using vacuum arc plasma deposition to create oxide cathodes. Several test depositions were done in order to develop expertise working with the highly reactive barium metal as a plasma source. Eventually, attempts to deposit barium on a clean silicon substrate met with success.

Following the success of the initial barium depositions, the UCD/SLAC/LBNL collaboration designed an experimental set-up whereby both the deposition and cathode activation could take place in the same vacuum chamber. A standard 1" diameter klystron cathode package was employed as the substrate for deposition of approximately 0.7 microns of barium oxide. Immediately following the deposition, the cathode was placed 0.5" from a planar copper anode/collector. The cathode was subsequently heated to temperatures between 770°C and 870°C where the pulsed current emission was monitored at cathode/anode voltage differences up to 2 kV. Results from this initial effort are shown in Fig. 2. Despite the thinness and nonuniformity of the coating, a maximum current of 1 A was achieved--well beyond expectations. The nonuniformity of the coating was due to the large size of the substrate surface compared to the plasma source (1" diameter substrate vs. a 1/4" diameter barium rod). Following the success of this proof-of-principle experiment, facilities for manufacturing and testing plasma

deposited oxide cathodes were assembled at UC Davis (and subsequently moved to SLAC) in order to further pursue this novel method for making oxide cathodes.

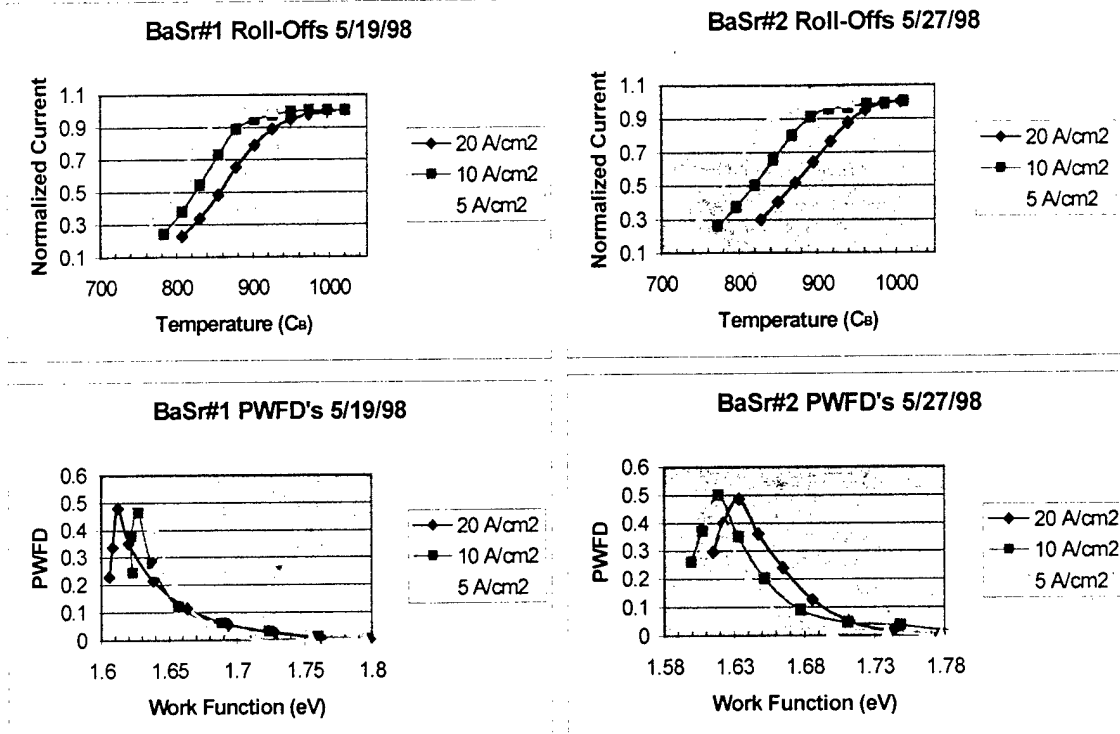


**Figure 2 Temperature limited current drawn from the first vacuum arc deposited oxide cathode at LBNL. Cathode temperature was approximately 815°C.**

The deposition is performed by generating a cathodic arc discharge at the surface of a barium or barium-strontium alloy rod. The metal plasma thus created is then deposited on the substrate which can be negatively biased to encourage implantation during the deposition process. The deposition is performed with sufficient background oxygen present to oxidize the highly reactive metal coating. The plasma deposition is monitored via a rate thickness monitor, an optical emission spectrometer for plasma composition information, and an electrostatic Langmuir probe for the determination of the plasma density and temperature profile. Cathodes thus produced are analyzed by drawing pulsed current at a constant voltage for various values of decreasing cathode temperature in order to generate practical work function distributions which provide an indication of the quality and expected life time of the cathode.

By carefully following the experimentally developed procedure, the UCD/SLAC collaboration is able to manufacture oxide cathodes capable of emitting greater than 30 A/cm<sup>2</sup> (testing at greater cathode loading was prevented not by poor cathode performance but rather by high voltage arcing inside the cathode-anode package). Such cathodes are made using only the 50/50 mix of barium and strontium; traditional oxide cathodes see a work function improvement with the addition of a small amount of calcium. Improved vacuum and control over the background gases may also yield further improvement on the lowest achievable work function, and, hence, the maximum achievable current density at a given cathode temperature. Two successful oxide cathodes have been made using the above process; Fig. 3 shows the roll-offs and practical work function distributions (PWFD's) of these two cathodes for various pulsed cathode loadings. This

work was presented at both the 1998 Microwave Vacuum Electronic Device conference in Monterey, CA, as well as the 1998 IEEE International Conference on Plasma Science in Raleigh, NC.



**Figure 3 Pulsed high current density emission data for the first two successful plasma-deposited barium/strontium oxide cathodes.**

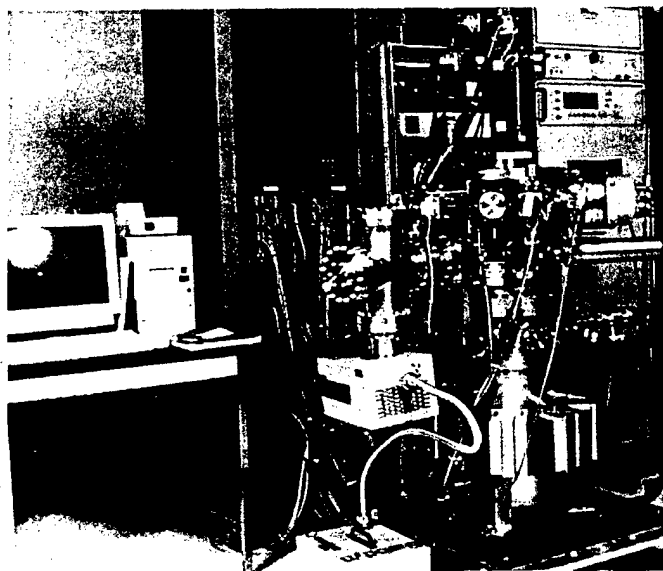
Exceedingly high water vapor partial pressure was most likely the cause for early failed attempts. Nevertheless, vacuum arc deposition has proven to be a novel, viable method for making oxide cathodes without the introduction of adhesives or binders that may later poison the cathode. In addition, the carbonate conversion/activation process may be nearly eliminated by depositing the coating in the presence of oxygen as long as there is a lack of available carbon to form any carbonates. These oxide cathodes are still very much in their infancy, and there may still be significant work function improvements ahead if greater control over the process cleanliness can be achieved.

In pursuit of the ultimate goal of a repeatable, reliable process for making an oxide cathode capable of emitting  $100 \text{ A/cm}^2$ , an evacuated transfer vessel is being manufactured at SLAC that will allow the user to coat an oxide cathode in the deposition chamber and subsequently transfer the cathode to a separate analysis chamber without ever exposing the cathode to ambient air. Once the transfer vessel is in operation, transferring the coated cathode to a cleaner chamber for analysis will remove the detrimental air exposure from the process steps. In addition, the lower base pressure of the analysis chamber will provide a more accurate picture of the best work function attainable with these oxide cathodes. The correlations shown between increasing water vapor pressure and decreasing cathode performance provide convincing evidence for the

importance of reducing the presence of water vapor in not only the analysis chamber but the deposition chamber as well.

To help achieve a lower water vapor partial pressure, ultra-violet lamps will be installed in the deposition chamber. Water molecules adsorbed on metal surfaces may be liberated from the surface given the energy of a UV photon. Such water molecules may subsequently be pumped out and removed from the vacuum system. Once this system is installed, it is expected that water vapor will be pumped much more readily and to a much lower base level.

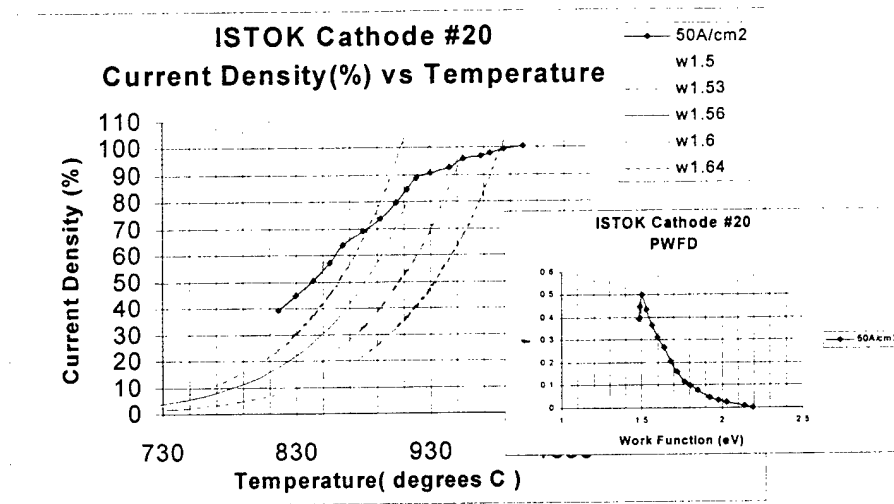
### Test and Analysis of Oxide Cathodes



**Figure 4** UHV Analysis chamber

A photograph of the ultra-high-vacuum analysis chamber now at SLAC funded under DURIP is shown in Fig. 4. Employing this UHV analysis chamber, a series of tests have been performed. A state-of-the-art oxide cathode from ISTOK in Russia was mounted in the life test vehicle and tested with the Miram Curve Generator. An extremely high emission current density of  $50 \text{ A/cm}^2$  was obtained at a cathode temperature below  $1000^\circ\text{C}$ . The emission data which is shown in Fig. 5 also matched the published Russian data. A Visual Basic program was coded to remotely control the Miram Curve Generator. The emission current roll-off curves (current density vs. temperature) and practical work function distribution curves for the cathode can now be obtained automatically by using this program. Two CPI carbonate oxide cathodes have been activated and tested in the analysis chamber. An attempt was made to reduce the poisoning effect by activating and testing the oxide cathodes in separate anodes. The activation anode is differentially pumped by a separate Turbo pump to ensure that binders and other potential poisoning materials do not enter the main chamber. Two RGAs are used to monitor the composition of the gas in the main chamber and the activation anode. Unfortunately CPI oxide cathode emission was only  $\sim 20 \text{ mA/cm}^2$ , probably because it

had been exposed to air for several months before testing. Auger analysis found a considerable amount of carbon on the surfaces, which indicated that they had



**Figure 5 Emission data for ISTOK oxide cathode.**

been poisoned. A Kelvin Probe (used to measure the cathode's average work function) has been tested and calibrated using a piece of aluminum. In addition, a new AUGER/XPS system with high energy resolution and SEM detector has been mounted on the analysis chamber. X-Ray Photoelectron Spectroscopy will provide more developed chemical state analysis of the cathode surface with minimal surface damage and no substrate charging problem. The SEM detector (with a video monitor) will provide an image of the cathode surface. Information about the composition uniformity of the cathode surface can also be obtained. A differential ion gun has been mounted on the chamber and will be used to etch the cathode surface to obtain composition depth profile information on the cathode surface. A 3-D beam analyzer has been mounted on the chamber to study the uniformity of the cathode emission. Following is a list of all the cathode test facilities on the UHV analysis chamber.

Cathode emission characterization test facilities:

- Miram Curve Generator (MCG)
- Separate activation and test anodes
- 3-D beam analyzer

Cathode Surface Analysis facilities:

- Kelvin Probe
- AUGER/XPS system with SEM detector
- Ion Gun sputter etching system

Other facilities:



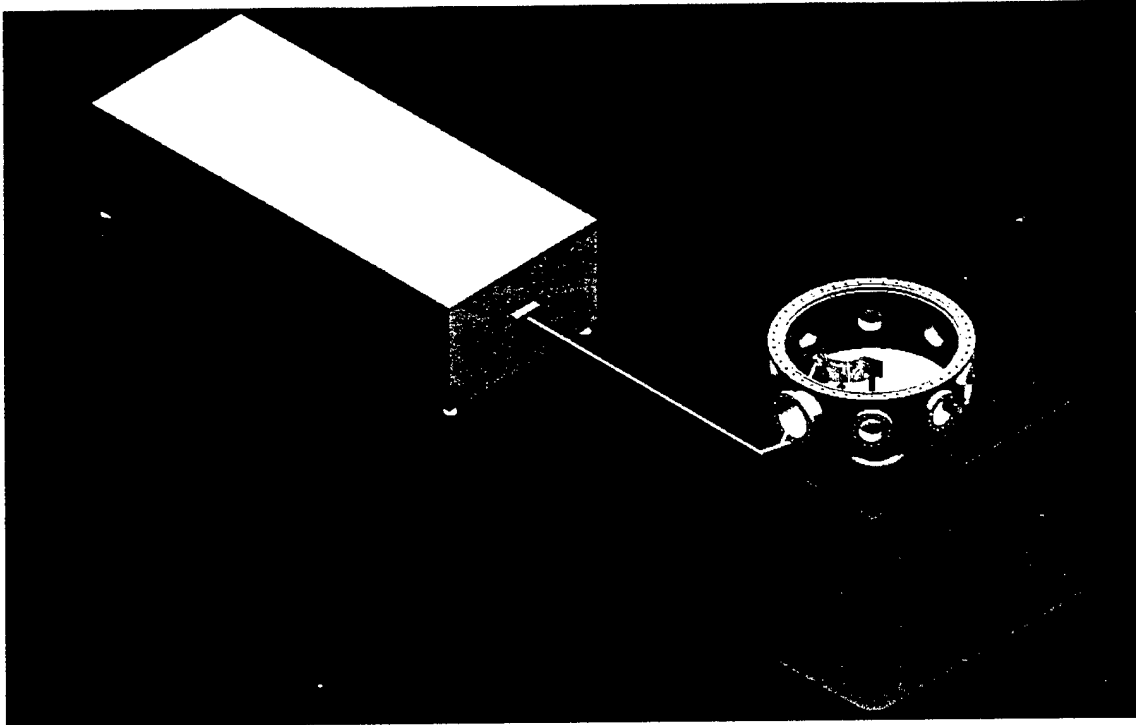
- Microcomputer/laser pyrometer
- Residual Gas Analyzer (RGA)
- Mechanical cathode transfer system

### **Vacuum Arc Plasma Gun in Ultra High Vacuum**

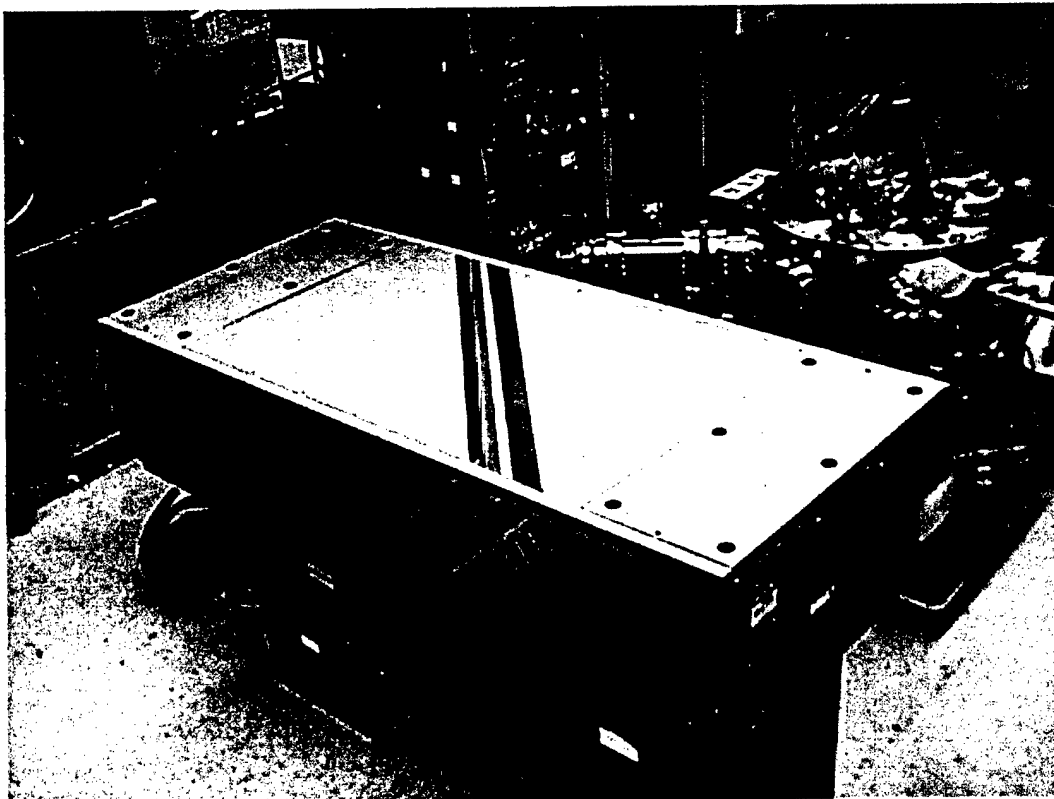
Initial results for the plasma deposited oxide cathode are encouraging. A peak current density of  $30 \text{ A/cm}^2$  was obtained with a cathode that had to be exposed to air during the setup for the emission test. Attempts to extend the cathode performance have been hampered by the deposition process. The plasma deposition process has encountered severe difficulties with the reliable operation of the plasma gun used to deposit the emission material on the cathode surfaces. The metal-vapor, vacuum-arc, plasma gun works quite well in a  $10^{-4}$  Torr to  $10^{-6}$  Torr vacuum. At those pressures, contamination of the deposited film by water vapor is very likely. In order to produce high-quality oxide-cathode emission films it is necessary to improve the vacuum by several orders of magnitude. In the deposition chamber at Stanford, the base pressure varies from  $10^{-8}$  Torr to  $10^{-10}$  Torr. This has made triggering of the plasma arc extremely unreliable to the point where most of the effort in the program this last year was dedicated to improving the plasma gun operating characteristics.

A DURIP proposal had been submitted in a prior year to purchase an excimer laser that would be used to either trigger the plasma arc or to replace the plasma arc entirely with laser ablation deposition. Although the original DURIP proposal was not funded, money from a previous DURIP grant became available to purchase the laser. A Lambda Physik excimer laser has been purchased. This device generates 700 microjoule pulses at up to 100 pulses per second. This is sufficient to vaporize the surface of the metal deposition material. If the vapor is sufficiently ionized by the laser beam, the plasma can be deposited directly. If the ablated material is not ionized sufficiently, a capacitor bank will be discharged through the plasma to achieve near 100% ionization. This laser triggered plasma deposition process should produce reliable deposition of emission films for oxide cathodes.

Figure 1 is a solid model showing the laser, the laser beam path and the deposition chamber. Figure 2 is a photograph of the laser with the deposition chamber in the background.



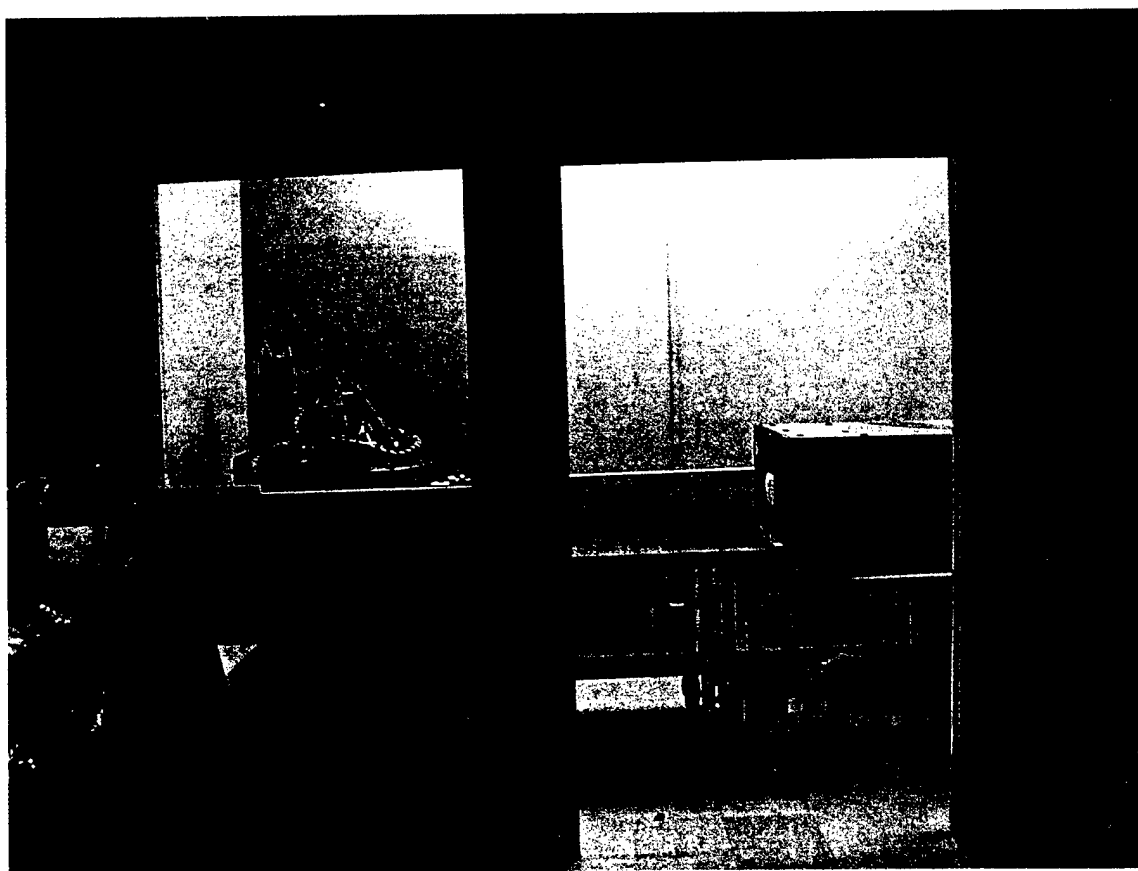
**Figure 1 Model of laser installation showing beam path and deposition chamber.**



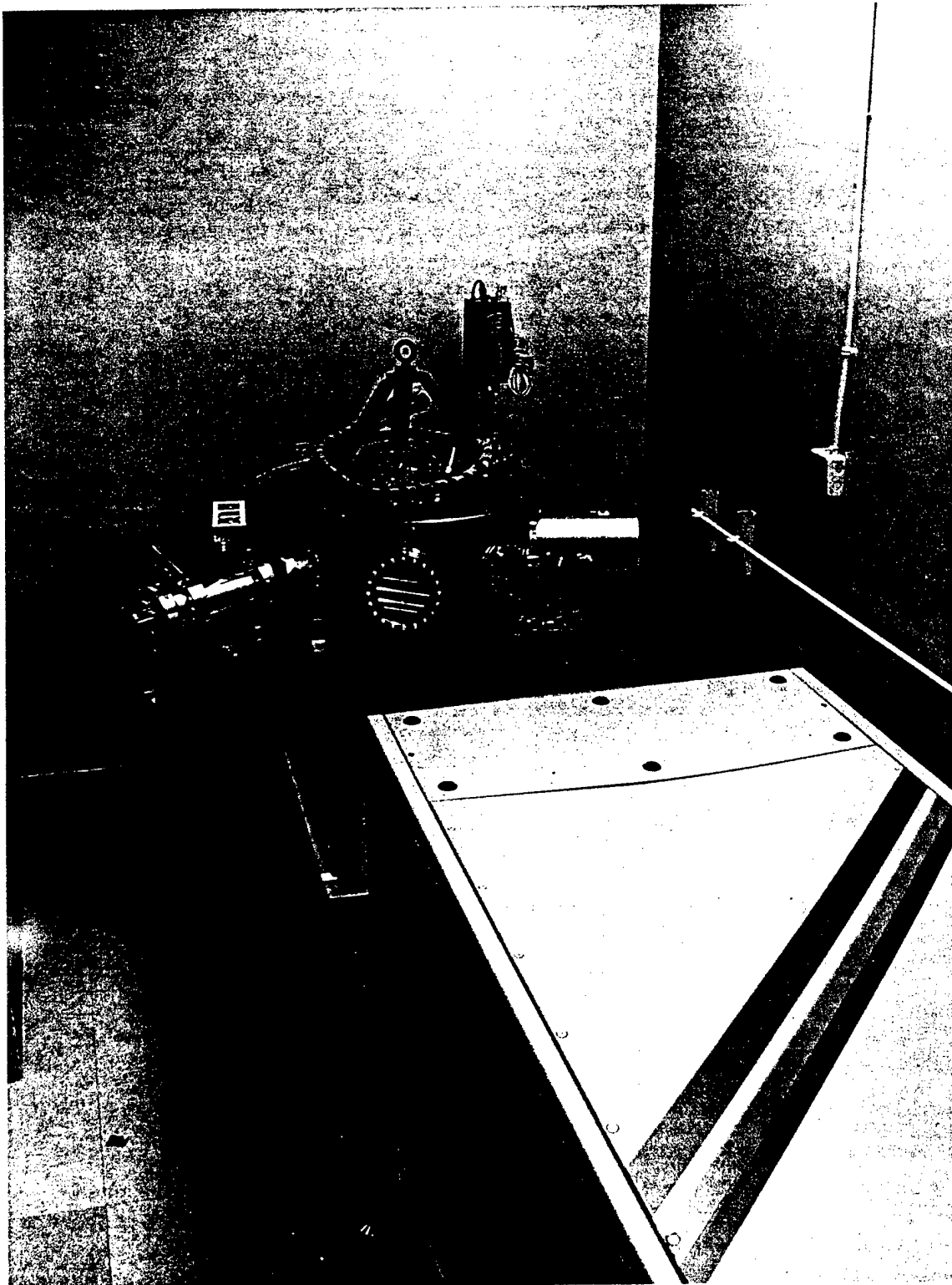
**Figure 2 Lambda Physik LPX 210 excimer laser with deposition chamber in background.**

In order to safely operate the excimer laser and its krypton-fluorine active laser medium, it was necessary to modify the oxide cathode laboratory layout. A laser room was constructed at the rear of the laboratory. The laser room is shielded so that no direct or scattered light from the laser can escape the room. In order to deal with possible emergency situations where the laser tube ruptures, a hole was cut in the roof of the building to duct the laser gases outside. Also two HEPA filters were installed to provide filtered air in the room to reduce production of ozone from the laser interaction with particulates in the air. The overhead crane trolley was relocated to the laser room to provide crane access for the deposition chamber, optical breadboard, and laser.

Photographs of the laser room and the setup of deposition chamber, optical breadboard, and laser are shown below. Approval for laser operation requires reviews by both the nonionizing radiation safety committee and the hazardous experimental equipment committee. The windows on the laser room wall and the entry door are made of either glass or Plexiglas. The attenuation through the glass at 248 nm is high enough to prevent exposure to the UV laser beam.



**Figure 3** Photograph of laser, optical breadboard and deposition chamber installed in laser room.



**Figure 4 Laser, optical table and deposition chamber in laser room.**

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